High Shear Force Chemical Mechanic Cleaning for CMP Defect Reduction

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High Shear Force Chemical Mechanic Cleaning for CMP Defect Reduction

- Post-CMP Cleaning Challenges for Advanced Nodes

- Concept of Chemical Mechanical Cleaning

- Cleaning Capability of Applied Pre-Clean Module
  - Pre-Clean Benefit Example: 3D NAND Thick / High Step Height ILD

- Addressing Post CMP Cleaning Challenges in LKP System
CMP Mechanism and Cleaning Challenges

- Three-body interaction: Wafer, Pad, Slurry
- Slurry: Complex suspensions containing abrasive particles, stabilizing agents and inhibitors
- Pad & abrasive remove inhibitor(a) from high pressure areas
- Remaining inhibitor(a) protects low areas.
- After polish layer cleared from stop layer, inhibitor(b) protects stop area and inhibitor(a) represses dishing of oxide in trenches
- Polishing by-products (chemical reactants, agglomerated slurry and pad/conditioner debris) are present on wafer after polish and needs to be removed during post-CMP cleans
Post CMP Cleaning Challenges

- Difficult to remove contaminants:
  - Slurry particles and polish residues
  - Organic components of the slurry
  - Pad debris

- Corrosion

- Multiple film materials exposed and new metals/liners/barriers (W, TiN, Co, Ru, ULK)

- Particle removal is more difficult with time

- Hydrophobic films, Philic / phobic surface combination

- Scratches on softer films

- Secondary contamination due to the “Loading” of the cleaning media

- Wafer edge cross-contamination

- Small particles become “visible” to metrology tools only after next film deposition
Examples of Defects Observed in CMP
Particle Removal

- Adhesion moment
  - Function of adhesion force (van der Waals), particle geometry
  - Proportional to particle radius

- Removal Moment:
  - Function of shear force, double layer interactions, particle geometry
  - Proportional to square of particle radius

For MR >1, a certain % of particles can be removed

Smaller particles are more difficult to remove
Smaller Particles are More Difficult to Remove
ILD0 (TEOS) Ceria Polish at 90 and 45nm

Defect comparison at >90 nm by SP2

Defect comparison at >45 nm by SP5-XP

Variability Gauge
Variability Chart for TEOS Post @90nm

Variability Gauge
Variability Chart for TEOS MTM Adders@45nm

Reference Process | High TPT process
Comparable performance: Reference vs High TPT

Reference process | High TPT process
High TPT process 5x worse than Reference

Small particle measurements capability reveals deficiency of the processes optimized with older metrology tools
Smaller Particle Removal Requires Advanced Capabilities
ILD0 (TEOS) Ceria Polish at 45nm

AMAT implements small particle measurements capability to optimize on-wafer performance for advanced nodes.
Particle Removal and Re-Deposition

**Particle Removal**

- Particle attached on wafer surface

**Breaking van der Walls forces:**
  - Undercutting by HF
  - Shear force by brush scrub, Megasonics, Fluid jet...

**Lift off by repulsive forces:**
  - Shear force by brush scrub, Megasonics, Fluid jet...
  - Electrostatic forces

**Particle Deposition**

- Van der Walls interactions: rapid deposition of particles close to the surface

- Diffusion of particles to surface due to overall attraction force and electrostatic force

- Particle removal: interaction force between the particle and the substrate has to be eliminated by shear force:
  - Fluid shear flow, Brush scrub, Megasonic cleaning, Fluid jet

- Chemical etching is used to assist with breaking the particle-surface bond
  - Undercut on the substrate and/or wet etch of the particle

- After breaking the bond, the particle has to be removed away from the surface to prevent re-attachment
Addressing Post CMP Cleaning Challenges in LKP System

- **Cleaner: 5x Side-by-Side Cleaner Stations**
  - **Megasonics**
    - Provides physical force to remove contamination from the features
    - Provides full wafer immersion tank for bevel contamination removal
  - **Pre-Clean**
    - Provides means to perform chemical buff in a dedicated slurry-free module
    - Vertical buff enables effective contamination removal off the surface
    - Enable cleaning of top surface of the wafer bevel
  - **Two consecutive brush boxes** provide high particle removal efficiency and precise brush pressure control
  - **Vapor Dryer** provides defect-free drying of hydrophilic, hydrophobic and mixed surfaces
  - **Cleaner Chemical Flexibility** enables particle undercut and lift-off
    - HF-compatible brush box enables SiO₂ substrate etching
    - Proprietary chemicals often include particle etch capability
Chemical Mechanical Cleaning

- Applied Materials Pre-Clean Module in Post-CMP Cleaner
- Use Pre-Clean module to remove strongly adhered defects
- Remove particles with controllable/uniform (in micro scale) mechanical force and chemical action at wafer/pad interface
Pre-Clean Benefit Example: 3D NAND Thick / High Step Height ILD

CMP Challenge

- Planarization for high incoming step height (um) at wide space (mm)
- Process drift during thick material removal (Long polish)
- Wafer bow (compressive) from thick film (stack, gap-fill) deposition

Approach

- Minimize polish time for process stability and low topography (Multi-Platen)
- In-situ remaining profile control for high rate non-Prestonian slurry (ISPC)
- Edge polish capability with Titan Head family
Multi-Platen Polish: Topography

- **Conventional:**
  - P1 Polish + P3 Buff
  - P2 Polish + P4 Buff

- **Multi-Platen:**
  - P1 Polish + P3 Polish
  - P2 Polish + P4 Polish
  - No room for buff

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Lower Topography and WID Range by Controlling Pad Temp and By-product

*Defectivity challenge: No platen available to perform Buff*
Ce Slurry Cleaning Challenge for High Oxide Removal CMP

- Ceria abrasive have significant surface chemical action during SiO$_2$ film polish
- Oxide removal rates are tunable by controlling ceria particle characteristics and the surface activation components
- High oxide removal characteristics of the slurry represent significant challenge for post CMP clean

Problem Statement:
High Ceria surface Contamination after CMP

Without Chemical Buff, ceria surface contamination remains high after conventional Brush Scrub
Ce Slurry Clean: Pre-Clean Parameter Optimization

**Pre-Clean Chemistry**

Pre-Clean buff with alkaline chemistry shows best defect performance, as expected based on Zeta-potential Diagram

<table>
<thead>
<tr>
<th>Process</th>
<th>Brush Clean Only</th>
<th>Plated Buff + Brush Clean</th>
<th>PreClean Buff + Brush Clean</th>
<th>PreClean Buff + Brush Clean</th>
</tr>
</thead>
</table>
Ce Slurry Clean: Pre-Clean Parameter Optimization

Effect of Wafer / Pad Rotation Speed

High rotation speed with mismatched wafer / pad speeds shows improved performance
Ce Slurry Clean: Polish and Clean Concurrent Optimization

Both Polish and Clean processes must be optimized to achieve best defect performance:
- Post Polish Wafer Rinse and IPC significantly improved defect results
- High shear rate Pre-Clean process ensures high particle removal efficiency
Ce Slurry Cleaning Solution for High Oxide Removal CMP

Customer previous approach:
Additional clean needed post CMP

Customer HVP Solution:
Chemical buff in Pre-Clean Module

High shear force Pre-Clean in CMP cleaner eliminates need for stand-alone post CMP clean

Customer HVP:
Increased Cost and Cycle time to avoid yield loss

Piranha Wet bench

Polish + Pre-Clean + B1/B2
< 100 @ 120 nm
BEOL Slurry Clean: Pre-Clean for Improving Particle Removal Efficiency

Pre-Clean effectively removes residues from hydrophobic ULK surface
BEOL Clean: Pre-Clean for Improving Particle Removal Efficiency

Pre-Clean removes particles and organic residue from Cu polished with a challenging slurry
Pre-Clean with Chemical Buff Benefits

1. For customers that use chemical buff on final platen - **FEOL**
   - Move platen chemical buff to Pre-Clean module in the cleaner
   - Enables multi-platen polish for Improved topography and WID range
   - If multi-platen polish is not required, enables significant throughput increase
   - Eliminate the need for additional stand-alone (e.g. wet bench) post-CMP cleaning step with high particle removal efficiency Pre-Clean module

2. For customers with organic residue or nano-defects – **FEOL/ BEOL**
   - Insert chemical buff with Pre-Clean module in the cleaner
   - Aggressive – Can remove many defects that roller brushes cannot
   - Flexible – Allows for chemistries not compatible with platen slurry

3. For customers with circular scratch issues – **BEOL**
   - Use Pre-Clean before roller brushes to reduce the amount of polish residue loading brushes, extending brush life and reducing excursions
Megasonic Cleaning

- Physical cleaning method utilizing sonic waves: the liquid undergoes alternating compression (high pressure) and rarefraction (low pressure) in a sinusoidal pattern relative to location and time
  - Nucleation occurs from small gas pockets
  - Cavities grow by rectified diffusion
  - Collapse releases significant amount of energy locally

Cavitation collapse near surface provides shear force for particle removal but can also cause damage
Brush Scrub: High Efficiency Particle Removal Clean

- Clean technology of choice for Post CMP cleans and general Clean applications
- Brush Material: PolyVinylAlcohol (PVA)
- Particle removal efficiency is a strong function of the shear force impacted by the brushes on the wafer
- As brush compression increases, brush pressure increases and shear force increases

\[
F_{\text{shear}} = \mu F_{\text{normal}} = \mu PA
\]
where \( \mu \) is the friction coefficient, function of RPM, chemistry, wafer surface, etc.
\( P \) is brush pressure
\( A \) is the area of contact = 2zL

\[
dF_{\text{shear}}(z) = 2\mu P(z)ldz
\]

\[
dT(z) = dF_{\text{shear}}(z)R = 2\mu P(z)Lrdz
\]

\[
Torque = \int dT(z)dz = 2\mu \int P(z)Lrdz
\]

\[
Torque = \mu P R 2zL
\]

Two consecutive brush boxes provide high particle removal efficiency and precise brush pressure control
Advanced Brush Pressure Control

Problem Statement
- Brush motor torque is related to the pressure that brushes apply to the wafer surface, and thus, the brush shear force and particle removal efficiency.
- At constant brush spacing set point, brush motor torque changes over the lifetime of the brush.
- In order to keep shear force constant, need to keep the average brush motor torque constant.

Success criteria:
- <5% error torque drift over brush life

Approach
- Brush Torque CLC algorithm maintains constant average brush shear force on wafer surface by dynamically changing brush spacing to keep brush motor torque constant.

Demonstrated capability to maintain constant brush pressure over brush life by dynamically changing brush spacing.
Brush Box Recipe Flexibility Required for Cleaning at Advanced Nodes

- DIW through brush core cleans out the brush
- Chemistry delivered to Wafer / Brush interface
- Flexible recipe allows for wafer rinse with chemistry without brush contact
- DIW splash back from the brush during rinse is mitigated with low brush RPM

No Dirty Liquid Dripping from the Brush onto the Wafer in Vertical Brush Box
Basic Principle of Surface Tension Gradient Drying

- Surface tension difference caused by surface IPA concentration gradient in DIW helps pull DIW from wafer surface
- Marangoni drying requirement: refreshing of IPA and DIW to keep the gradient

Vertical Marangoni Dryer provides defect-free drying of hydrophilic, hydrophobic and mixed surfaces
Addressing Post CMP Cleaning Challenges in LKP System

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- Multiple film materials exposed and new metals/liners/barriers (W, TiN, Co, Ru, ULK).
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- Secondary contamination due to the "Loading" of the cleaning media.
- Wafer edge cross-contamination.

5 consecutive cleaning stations
High shear force Pre-Clean
Megasonic option
Two Brush Boxes
Dryer

Flexible chemistries
Brush box recipe flexibility

Inter-Platen Clean
Chemistry in HCLU Option

Vertical Marangoni Dryer
VD1.5 Dryer enhancement

Contamination removal in Pre-Clean
Advanced brush pressure control

Buff pad conditioning in Pre-Clean
BB2.0 brush conditioning in brush box

Wafer top-bevel Clean in Pre-Clean
Bevel clean in immersion Meg tank
Summary

- Geometry shrinking and new material implementation in advanced nodes demand the achievement of high particle removal efficiency.

- Chemical Mechanical Cleaning combines controlled mechanical force with chemical action to remove strongly adhered particles and residues, without sacrificing film stack integrity.

- To address cleaning challenges in various nodes, Applied CMP implements:
  - High shear force Pre-Clean module for high defect removal efficiency
  - Single wafer Megasonic module for improving defect removal efficiency
  - Dual brush box module with advanced process control
  - Single wafer IPA dryer for achieving water-mark free drying